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Asynchronicity of fine sediment supply and its effects on transport and storage in a regulated river

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Abstract

Purpose A disconnected ephemeral tributary was reconnected to the regulated River Ehen (NW England) as part of a river restoration initiative, providing a renewed delivery of sediment to a highly stable and armoured channel. This paper (1) assesses spatial and temporal dynamics of suspended and stored sediments in the Ehen, (2) characterises the composition of stored sediment, (3) develops fine sediment budgets for downstream river reaches, and (4) assesses the controls on the storage of fine sediment in the riverbed.

Materials and methods A 3-km study section in the upper part of the River Ehen was divided into two reaches. Suspended sediments were monitored at the downstream limits of each reach over a 2-year period. In-channel storage was measured in three morphological units within the upper reach, on 13 occasions over the same period. Samples were used to assess changes in volumes of stored fine sediment, as well as the grain sizes and organic content of the material. A time-lapse camera facing the confluence of the tributary was used to conceptualise different flow scenarios. These scenarios reflect the degree of synchronicity between flows in the main-stem and those in the tributary. Fine sediment budgets were developed for each reach to assess the relative contribution of different sources of sediment.

Results and discussion The reconnection significantly affected suspended sediment loads in the Ehen. Bed storage increased twofold, with changes most evident in the slow-flowing morphological unit. Changes in the composition of stored sediment were less marked than changes in the quantity of material. Changes in bed storage were controlled by the degree of synchronicity between flows in the Ehen and those in the newly reconnected tributary. Results show that three generalised flow scenarios occur, with total asynchronicity between flows in the tributary and the Ehen being responsible for the main episodes of fine sediment deposition. Overall, the estimated sediment budgets provide insights into the importance of non-perennial sources of sediment in supply-limited systems such as the Ehen. Although bed storage values are within the range of those published for UK rivers, the increase observed since the reconnection, together with the persistence of a static pavement, highlights the ecologically critical conditions of the regulated main-stem River Ehen.

Conclusions Intermittent sources control fine sediment transport dynamics in the upper River Ehen. In this regulated river, ongoing deposition associated with increased low- and medium-sized flow events exerts more of a control on bed storage than large but rare floods. Management actions to limit delivery of material from lateral sources could help prevent further deterioration of habitat conditions for biota sensitive to fine sediment. Given the ongoing adjustment in the newly reconnected tributary, continued monitoring is needed to capture further morphosedimentary response in the main-stem.

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1 Introduction

The storage of fine sediment within the gravel matrix of river and stream beds represents an essential component of the sediment budget of river basins (Trimble 1983). Sediment stored in-channel varies in quantity and quality over time and space, in response to sediment input from the basin (Wilson et al. 2004), local geomorphological conditions (e.g. particle mobility, grain size, surface sorting and texture; Milhous 1973; Adams and Beschta 1980; Frostick et al. 1984; Walling and Quine 1993) and the nature of the flow regime, including both temporal and spatial variation in hydraulics (Diplas and Parker 1985). The characteristics of the fine material also influence its transport and storage dynamics (e.g. fall velocity and Reynold's number of the particles; Diplas and Parker 1985). Thus, as not all the material produced and transferred to the drainage network reaches the basin's outlet immediately (Reid and Dunne 1996; Walling et al. 1998), fine sediment transport is best considered an intermittent process.

Large proportions of the fine sediment load transported by rivers are conveyed in short periods of time, during major competent events. However, new material delivered from the catchment is not always the main source of sediment during such events—the resuspension of material stored temporarily in the channel can increase the magnitude and frequency of suspended sediment transport (e.g. Petticrew et al. 2007; Navratil et al. 2010) and can control transport during periods between floods (Smith and Dragovich 2008). The scale of removal of sediment stored on the bed depends not only on flow conditions but the depth and cohesive properties of the material (Diplas and Parker 1992). Consequently, understanding patterns of in-channel sediment storage is critical for elucidating the sediment dynamics of a river, whether focused on the reach (e.g. Smith et al. 2003; Collins and Walling 2007a) or network (e.g. Walling et al. 1998; Wilson et al. 2004) scale. As fine sediment deposition is well known for having marked biological effects (Wood and Armitage 1997; Bilotta and Brazier 2008; Buendía et al. 2014), understanding fine sediment dynamics is also critical for assessing the factors influencing river ecological status (Buendía et al. 2013a, b).

Excessive volumes of fine sediment are most problematic for species that live buried within the subsurface zone for a part or the whole of their life cycle (e.g. salmonids, Soulsby et al. 2001; Greig et al. 2005), where clogging can impact oxygen supply. Fine sediment deposition is especially important for those organisms that are fully sessile or less mobile, because they have no means of immediate escape at the time-scale of depositional events. For example, the freshwater pearl mussel *Margaritifera margaritifera* (L.) is threatened by a range of anthropogenic instream habitat changes, but is particularly vulnerable to the effects of fine sediment deposition (see review by Quinlan et al. 2015b). Although the debate is still ongoing about whether the effects of fine sediment are primarily caused by its physical (e.g. clogging) or chemical properties (e.g. Biochemical Oxygen Demand; Quinlan et al. 2015b), it is clear that fines influence mussel survival and recruitment (Bauer 1988; Buddensiek et al. 1993; Geist and Auerswald 2007; Tarr 2008). Thus, gathering information on the characteristics and dynamics of fine sediment (its grain size distribution, organic content, temporal patterns of storage and conveyance) is important to better assess the quality of riverbed habitat for aquatic organisms (Österling et al. 2010; Quinlan et al. 2015b).

Collecting empirical data on in-channel fine sediment storage is constrained by the highly variable nature of the river environment and the technical limitations of sampling methods (Diplas and Parker 1992). Conventional approaches comprise indirect and direct methods (Collins and Walling 2007a). Indirect methods rely on comparison of suspended sediment loads for upstream and downstream locations, to infer changes in sediment storage within the reach (e.g. Miller and Shoemaker 1986). Direct methods include core sampling, sediment trapping and resuspension of stored material. Of these, the resuspension method first presented by Lambert and Walling (1988) is being used increasingly (e.g. Collins and Walling 2007a; López-Tarazón et al. 2011; Piqué et al. 2014); it has been shown to perform well across different types of substrate and provides valuable information on material stored in both the surface and subsurface zones, as well as its size characteristics (Duerdoth et al. 2015).

This paper reports the results of work undertaken to understand fine sediment transport and storage dynamics in an ecologically important river. The river (the Ehen, NW England) is the focus of a major restoration project, designed to conserve its important pearl mussel population. The restoration project includes the re-naturalisation of the hydrological regime of the Ehen and the reconnection of an ephemeral tributary, Ben Gill, to help reinstate more natural (dynamic) fluvial processes. The objective of re-introducing coarse sediment into the Ehen from this tributary is already being achieved (Marteau et al. 2016). However, recent work has shown that much fine material is also being delivered, and since its reconnection, the tributary has become the main driver of fine sediment dynamics in the river system (Marteau et al. 2017). The timing of water and sediment delivery from the tributary does not always coincide with competent flows in the Ehen, leading to important differences in suspended sediment concentrations, with potential implications for the quality of benthic habitat of mussels. The aim of this paper is therefore to better understand the dynamics of fine sediment transport and storage in the 3-km section of the main-stem Ehen immediately downstream from the tributary. This section supports high mussel densities and so is considered critical for the population. Specific objectives of the paper are to (i) examine the spatial and temporal dynamics of suspended sediment loads in the study section, (ii) assess the characteristics of the fine sediment stored in the upper reach, (iii) develop fluvial sediment budgets for two contrasting reaches within the study section and (iv) characterise the flow scenarios that control in-channel storage in the River Ehen.

2 Materials and methods

2.1 Study area and context

The River Ehen (NW England) is home to the largest remaining population of freshwater pearl mussels in England. The Ehen is typical of many pearl mussel rivers in that the population of this important species faces many threats (Young et al. 2001) and has experienced limited recruitment over the last 20 years (< 1%, O'Leary 2013), resulting in an ageing population. Habitat conditions in the upper River Ehen were described by Quinlan et al. (2015a) as being suboptimum for mussels due to compaction and stability of the riverbed and the extremely limited movement of the surface layer.

The Ehen and its tributaries drain a total catchment of 155.8 km^2, with the upper part of the catchment mainly represented by the River Liza and Ennerdale Water (Fig. 1b). Flows in the Ehen are regulated by Ennerdale Water (a post-glacial lake) and its associated weir (Fig. 1c). This regulation mostly affects low and peak flows. In order to improve local water supply, the weir was heightened (to 1.3 m) in the 1970s and an ephemeral stream (Ben Gill, the main headwater tributary) was diverted to the lake. For over 40 years, the River Ehen has therefore been deprived of water and sediment from this tributary, leading to rising concerns over habitat suitability for mussels and their hosts (Atlantic salmon *Salmo salar* L. and brown trout *Salmo trutta* L.). This prompted the decision to reconnect Ben Gill to the Ehen as part of the restoration initiative underway across the catchment.

Ben Gill (Fig. 1c, d) is an ephemeral first order headwater tributary which drains a small (0.55 km^2) but steep catchment (average slope 25%). The upper part of the catchment is covered by shallow acid grasslands with heather and bracken, overlying the remains of glacial tills. The channel then runs over a series of waterfalls and step-pool sections, where it forms a steep gully. This upper part represents *c.*85% of the length of the channel and has always remained unaffected by the diversion. When reaching the valley floor, the channel flattens out and runs through an old alluvial fan. In the 1970s, Ben Gill was diverted at the break in slope between these two sections (the fan apex), with water conveyed to the lake via an underground culvert. Coarse sediment delivered from the upper section accumulated around the diversion point and was periodically removed from site. As a result, the lower section (*c.*15% of the overall channel length) has filled-in and gradually terrestrialised. The reconnection of Ben Gill involved the creation of a new *c.*300-m long section of channel through the alluvial fan, following its approximate original course. This section of channel was designed to be 5-m wide and 0.5-m deep, and lined with cobbles and boulders.

Since its reconnection in October 2014, Ben Gill has been delivering relatively large amounts of fine sediment but limited volumes of water to the Ehen. The timing of sediment delivery does not always coincide with high flows in the Ehen (Marteau et al. 2017), potentially leading to high rates of deposition downstream from the confluence.

This study focuses on the upper section of the Ehen, immediately downstream from Ennerdale Water (Fig. 1c) and the confluence of Ben Gill.

Bleach Green Gauging Station is in the middle of the study section, where the catchment area is 44.5 km^2. Ben Gill enters the Ehen immediately downstream from Ennerdale Water; the reach between here and the Gauging Station is 0.55 km long and has a relatively low sinuosity (1.2). Prior to the reconnection of Ben Gill, the bed of this reach was extremely stable, with a static armoured layer capable of resisting bankfull flows (Quinlan et al. 2015a). The lower part of the study section (the 2.52 km reach downstream from the Gauging Station) has a different planform (sinuosity 1.97). The Oxbow (Fig. 1c) represents the lowermost point of the study section; here, catchment area is 47.0 km^2 (i.e. 2.5 km^2 more than at the Gauging Station, and 3.0 km^2 more than at Ennerdale weir). No previous studies have assessed bed conditions in this lower reach. It differs from the upper reach in receiving water and sediment from drainage ditches and a number of small non-perennial tributaries.

2.2 Data acquisition and monitoring

2.2.1 Discharge and flow conditions

Bleach Green gauge is operated by the Environment Agency (EA) and records discharge (Q) at 15-min intervals (Fig. 1c, d). The accuracy of this gauge was not specifically assessed, but is estimated to have a maximum error of ± 8% (Sauer and Meyer 1992). The current study covers a period of just over 2 years, from July 2014 (3 months before the reconnection of Ben Gill) until August 2016. Discharge data for the Gauging Station (15-min interval) were used to produce flow time series for the study period and estimate water yield. Mean daily values for the 1974–2016 period were used to compute flow percentiles, to help set the study period within a longer-term context.

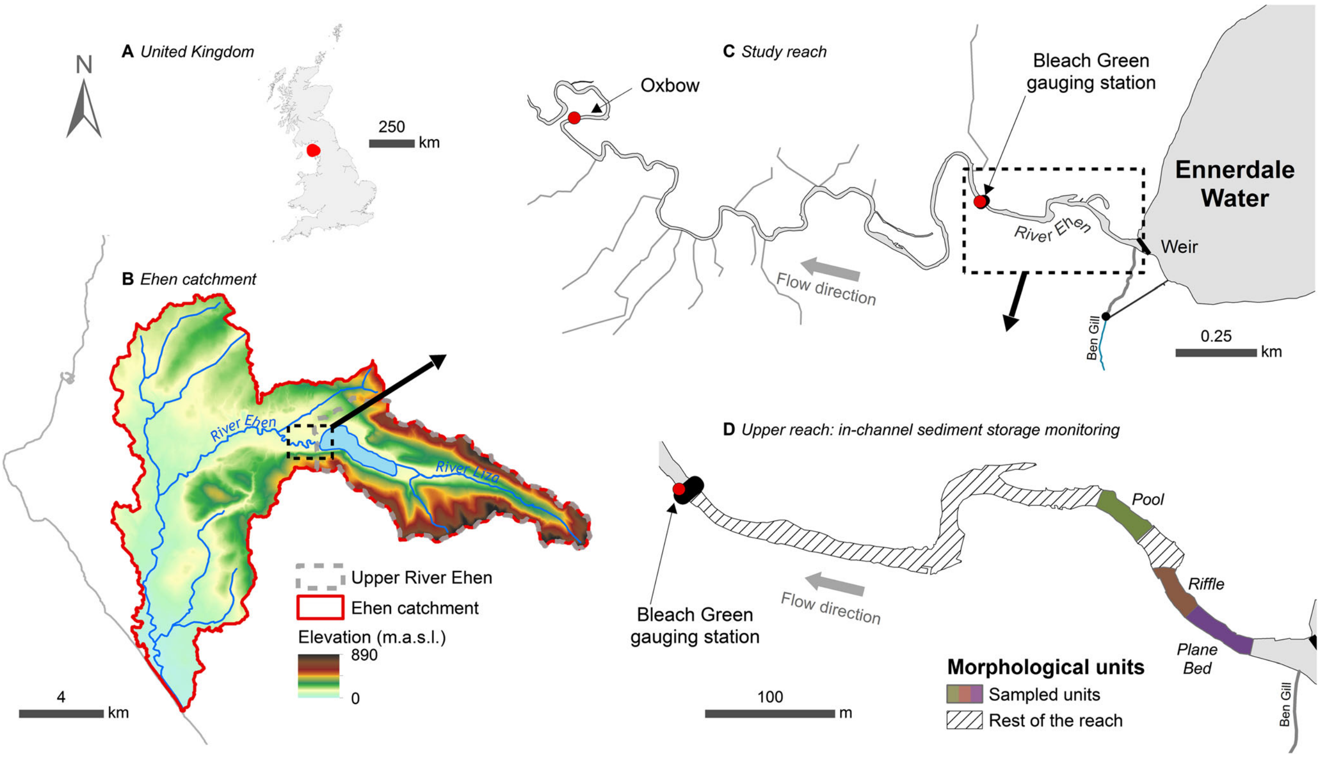

Fig. 1 Location of the River Ehen study area. **a** Within the UK. **b** Digital Elevation Model of the Ehen catchment. **c** The entire study section where suspended sediment was monitored. **d** The main (upper) study reach were in-channel sediment storage was monitored

Ben Gill is not gauged, although Quinlan et al. (2015a) reported that over their 18-month monitoring period, it flowed for approximately 23% of the time. Information on flow conditions in Ben Gill during the present study were collated from a variety of sources. Between June 2014 and June 2015, information from staff from the agencies involved in the restoration project (EA, Natural England, United Utilities and engineering contractors) was collated to determine whether Ben Gill was flowing. Because of the engineering work being undertaken in Ben Gill and Ennerdale Weir, contractors were on site on a more or less daily basis and so records for this 1-year period are comprehensive. In June 2015, a time-lapse camera was installed to record flow events in Ben Gill (1-h interval), so for the second part of the study period, continuous records are available. The camera was positioned on the true right bank and faced in the direction of Ben Gill confluence, allowing inspection of flows in Ben Gill as well as whether Ennerdale lake was overtopping the weir. Images and information from staff notes were used to estimate the number of days that Ben Gill was flowing, and hence the timing and duration that it was delivering water and sediment to the Ehen.

2.2.2 Suspended sediment

Suspended sediment concentration (SSC) in the Ehen was calculated from turbidity (NTU) recorded using YSI® 6600 probes with self-cleaning wipers. These probes have a 0.1 NTU resolution and ± 2% or 0.3 NTU accuracy (whichever is greater). One turbidity probe was located at the Gauging Station (Fig. 1c, d) and placed directly in the water column, logging at 15-min intervals. A second probe was installed at the Oxbow, also placed directly in the water column and logging at 15-min intervals. Both probes were maintained by EA, and retrieved for cleaning and calibration every 2 to 3 months.

An empirical NTU-SSC relationship was produced to compute SSC from turbidity readings (see Marteau et al. (2017) for more details). This relationship was developed using fine sediments transported during floods. Water samples were collected during flood events and brought to the lab, where they were concentrated and/or diluted to prepare samples of known SSC. Samples used covered the entire range of the turbidity probes. Because the probes were regularly retrieved and swapped around, and since they were all re-calibrated in the same lab against the same standards, a single NTU-SSC relationship was developed and used for the two monitoring stations. The standard deviation of the residuals from the linear regression representing this relationship was 0.9; this standard deviation was used to assess error in suspended loads. The organic fraction of total suspended sediment was rather low (below 10% on average), with no apparent seasonal or annual variations. The highest values of organic matter were measured at very low SSCs and so could not be differentiated from uncertainties associated with sample processing and probe accuracy. Thus, no attempt was made to correct SSC values for organic matter.

Suspended sediment loads (SSL) were calculated by multiplying SSC by Q at a given time-step (15 min). Due to good mixing, the use of a single probe was adequate for calculating SSC and SSL for each monitoring station. Data available were not sufficient to provide a detailed uncertainty analysis for SSL estimates. To provide an approximation of uncertainties, an average error (E_{SSL}) was determined considering the three main sources of error. The first source of error is the one associated with the turbidity sensors (E_S), for which the accuracy provided by the manufacturer was used (± 2%). Second, errors associated with the measurement of discharge (E_Q) were considered, following Sauer and Meyer (1992), as being of ± 8%. Finally, the last source of error identified stemmed from the empirical NTU-SSC relationship (i.e. E_R, the standard deviation of residuals from the linear regression (± 0.9%)). These three sources of error were used to estimate the average total error (E_{SSL}) following the standard error propagation:

$$E_{SSL} = \sqrt{\left(E_Q\right)^2 + \left(E_S\right)^2 + \left(E_R\right)^2} \tag{1}$$

The E_{SSL} is used to provide a value of uncertainty (±) for SSL and sediment yield estimates.

Finally, from the SSC and SSL data, duration curves and cumulative yields were produced for the whole study period, as well as for individual seasons. Seasons were considered to extend for 3 months; they began with summer 2014, covering July, August and September 2014, and so on.

2.2.3 In-channel fine sediment storage

Storage was monitored in the upper reach, between the confluence of Ben Gill and the Gauging Station (Fig. 1d). Bed substrate here consisted mainly of gravels and pebbles, with occasional cobbles. Fine sediment was considered as particles with a diameter < 2 mm, including sands (200–63 μm), silts (63–3.9 μm) and clays (3.9–1.2 μm) (Wenworth Scale, as per Bunte and Abt 2001). Note that the minimum range of the clay corresponds to the pore size of the filters used for laboratory processing. Storage was determined using the resuspension technique of Lambert and Walling (1988). This method involved isolating a patch of the bed using an open-ended plastic cylinder (diameter 0.43 m and height 0.65 m), which was carefully placed on the surface of the bed and held tight by pressing down on the handles, creating a seal. A layer of foam around the bottom of the cylinder helped ensure a tight seal with the riverbed. Stored sediment was then sampled within the area isolated by the cylinder (0.145 m^2) by disturbing the water and sediment with a shovel. Disturbance was at two levels: 1, only the water column was stirred actively (for *c.*30s) to re-suspend the fine sediment on the surface of the bed (agitation A1); 2, the top *c.*10 cm of gravel was energetically disturbed (for *c.*30s) to re-suspend any remaining surface sediment together with the fines contained in the top layer of the sediment matrix (agitation A2). Water and associated suspended sediments were collected in 0.5 l bottles for each agitation (one sample for A1, two replicate samples for A2). The sediment content of these samples was assumed to reflect the remobilisation of fine sediment covering the surface and contained within the bed material matrix, respectively. In addition, one complementary water sample was collected prior to the agitation process and used as a blank (i.e. to determine the ambient SSC to be subtracted from A1 and A2 samples).

Stored sediment was sampled on 13 occasions over the study period, timed to reflect potential changes related to flow. Three morphological units (pool, riffle and plane bed) were sampled on each occasion, with five samples collected from each unit (i.e. 15 samples in total on each occasion). The five samples were positioned to capture potential spatial variability within each unit (distributed as up- and downstream, left and right hand-side, and centre of each unit). Sampling locations were kept similar over the study period but, to avoid sampling a patch that was previously disturbed, were not identical. This sampling design yielded a total of 780 samples from which in-channel fine sediment storage was assessed.

Water samples were filtered using 1.2-μm Whatman® glass microfiber filters and dried in an oven for 12 h at over 65 °C. Subsequently, filters were weighed to determine sediment concentration. The amount of sediment stored per surface area unit U (in g m^{-2}) at a given location i was calculated as follows:

$$U_i(t) = \frac{C_i(t).V_i(t)}{S} \tag{2}$$

with the suspended sediment concentration C_i (in g l^{-1}) measured in the laboratory and associated with each level of agitation, the volume of water V_i (in l) determined from the depth of the water column above the bed and the area S (in m^{-2}) covered by the cylinder. In this case, C_i was calculated by integrating the two different levels of agitation after subtracting concentration from the blank. Thus, there is no differentiation between the surface and subsurface storage.

To determine the organic content of the samples, filters were subsequently placed in a furnace for 3 h at 550 °C to burn-off all organic matter (i.e. loss on ignition method LOI, %). Because of the small amount of sediment collected for some of the samples, the weight of the remaining inorganic fraction was corrected for potential loss of weight from the filter during the LOI process, by burning a series of blank filters throughout the lab processing period for comparison.

Finally, the remaining (inorganic) sediment was carefully scraped off the filters and processed with a Laser Particle Analyser (LS 13320, Beckman Coulter Inc.®) to measure the volumetric size distribution of the material.

2.2.4 Data processing and analysis

Sediment storage for a given morphological unit and sampling date was calculated as the average of the five samples. Following López-Tarazón et al. (2011) and Piqué et al. (2014), sample data were then extrapolated to estimate total storage in the whole of the upper reach (i.e. between Ben Gill and the Gauging Station). For this, the area of the reach occupied by each of the three morphological units was first assessed during low flow conditions; 29% of the reach was classified as riffle, 34.6% pool and 36.4% plane bed. Mean storage values (t m^{-2}) for each sampled unit were then multiplied by respective areas (m^{-2}) to estimate total storage (t) across the reach, using the following:

$$S_s = \sum_{i=1}^{3} U_i * A_i \qquad (3)$$

where U_i is the average sediment released at a given morphological unit i (t m^{-2}), and A_i is the area of the channel bed at unit i (m^2). Uncertainties in the estimates of in-channel sediment storage were determined using the 95% confidence interval.

Separate suspended sediment budgets were computed for the two reaches (Upper = Ben Gill to Gauging Station, lower = Gauging Station to Oxbow; Fig. 1). The two monitoring stations (at the Gauging Station and the Oxbow) allowed assessment of the differences in SSL and, consequently, the relative contribution of different sources of sediment to the sediment yield at the outlet of the study section (Oxbow monitoring station). For the upper reach, the information used to build the sediment budget consisted of suspended sediment yield at the output (i.e. Gauging Station) and in-channel sediment storage extrapolated over the reach. Additionally, information from previous published work (Marteau et al. 2017) showing the fraction of sediment yield delivered by Ben Gill, the only tributary flowing into this part of the river, was used. The sediment budget for the lower reach was built using input and output suspended sediment yields (i.e. Gauging Station and Oxbow monitoring stations, respectively).

Flow and suspended sediment characteristics were assessed during sampling periods which are represented as boxes and letters in Fig. 2. The main flow parameters used to help interpret sediment dynamics were mean Q, peak Q, number of flood events, and water yield in the Ehen. The main sediment parameters analysed were mean SSC, peak SSC, mean SSL, peak SSL and sediment yield (SY). Additionally, information about the frequency and duration of flows in Ben Gill (i.e. whether this sediment source was connected, and for how long) was summarised for each sampling occasion using the time-lapse images.

To test for significant changes in in-channel storage over time and space, two-way ANOVAs on ranked data were performed. Principal component analysis (PCA) was used to help assess spatiotemporal patterns in several parameters (volumes of sand, clay and silt; particle size quantiles and median (D_{90}, D_{50} and D_{10}), the proportion and total amount of organic matter, and the total amount of stored sediment). This analysis used standardised data and provided information on changes in the characteristics of stored sediment over time and differences between morphological units; it also provided information on the parameters changing or differing most, as well as any correlations between them. All analyses were performed with the software R v.3.3.3 (R Core Team 2017).

3 Results

3.1 Hydrological conditions

As reported previously (Quinlan et al. 2015a; Marteau et al. 2017), the hydrological regime of the River Ehen remains relatively variable and flashy, despite being regulated by Ennerdale Water and the weir (Fig. 2a). Patterns in flow are typical for the NW of England; lower flows occur in summer and higher flows in winter, but with some high flow events in late spring. Discharge for the study period ranged from 0.31 m^3 s^{-1} (11/02/2015) to 54.0 m^3 s^{-1} (15/11/2015, 30-years return period); mean and median discharges were 3.50 and 1.99 m^3 s^{-1}, respectively, which are slightly higher than long-term respective values (2.72 and 1.38 m^3 s^{-1}, 1974–2016). It is noticeable that flows in November and December 2015 were particularly high (i.e. third highest discharge recorded), as a result of excessive rainfall experienced across the region. Flows were around compensation flow (i.e. 0.92 m^3 s^{-1} ± 10%) for about 21% of the time, with some prolonged periods of low flow (e.g. mid-May to mid-July 2016).

Hydrological conditions between successive sampling occasions varied considerably (Table 1). Flow events were considered as being those when discharge increased over 1.5 times the baseflow. In total, 18 high flow events were recorded during sampling period i, partly due to the long time-span of this period but also because of precipitation which resulted in frequent increases in discharge (notably in November and December). Conversely, period g had lower Qs, with a peak of 2.10 m^3 s^{-1} and no high flow events.

Ben Gill flowed for an estimated 19.4% of the time, slightly less than during the period covered by Quinlan et al. (2015a). Flows in Ben Gill responded rapidly to local rainfall events, but recession was also quick; periods of flow lasted from just few hours to few days. The average duration of flows was 30.4 h, with a minimum of 1 h and a maximum of 13 days.

3.2 Suspended sediment transport

The Gauging Station is located approximately 600 m downstream from the confluence, with SSC data for here used as an index of input from Ben Gill; there is no other tributary in this

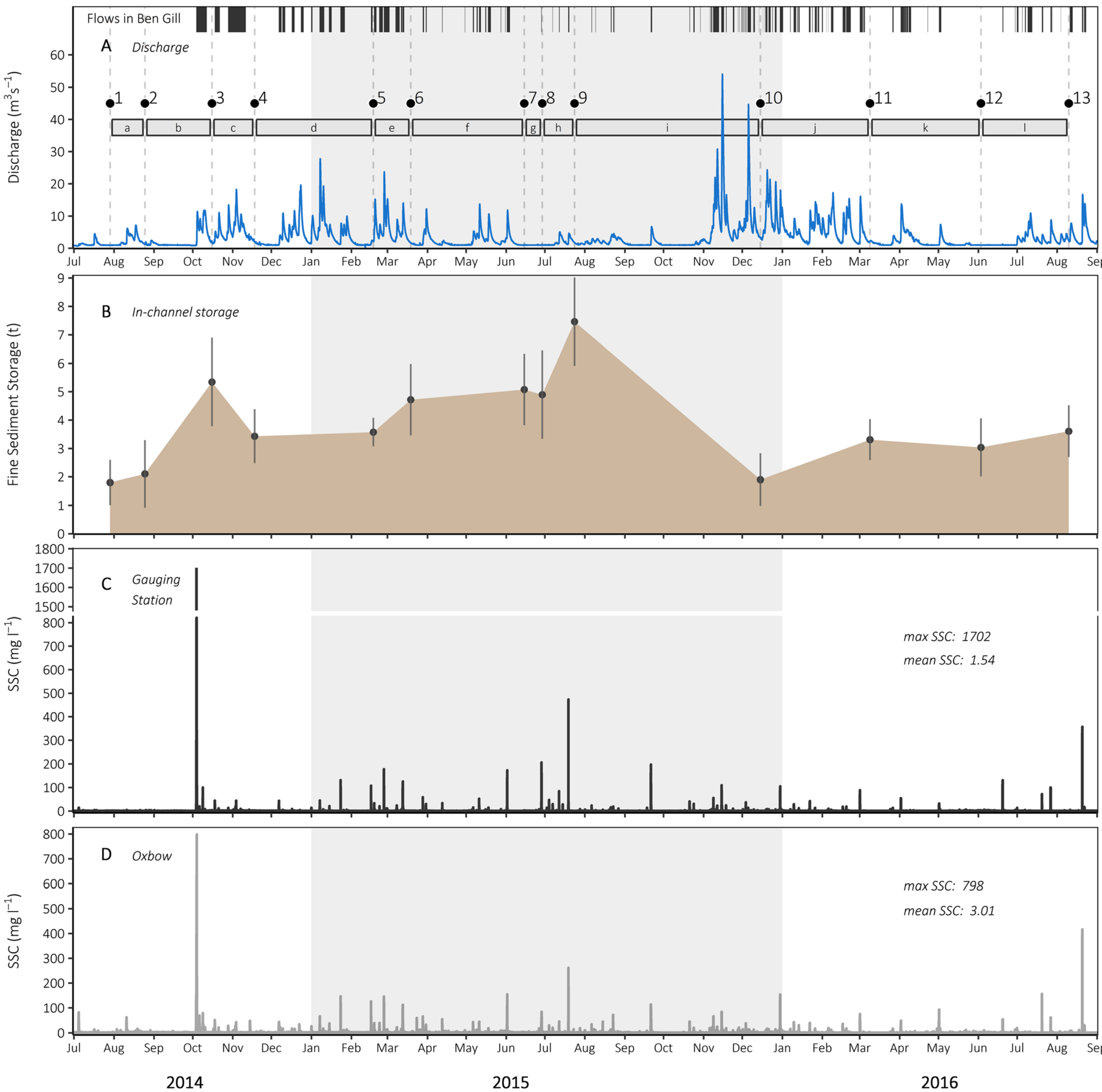

Fig. 2 Overview of the hydrological and sedimentary conditions in the River Ehen during the study period. **a** Discharge, as measured at the Gauging Station (blue, bottom), and flows in Ben Gill (black, top). The dots and numbers refer to in-channel storage sampling occasions, while boxes and letters refer to sampling periods. **b** In-channel sediment storage, calculated following the extrapolation described in the Methods section. **c** Suspended sediment concentration (SSC) at the Gauging Station. Note that to show the full range, there is a break in the *y*-axis between 800 and 1500 mg l^{-1}. **d** Suspended sediment concentration at the Oxbow. See Fig. 1 for details of location

reach and the assumption is that lateral inputs -other than bank erosion- are negligible.

The Gauging Station showed no major episode of high SSCs prior to the reconnection of Ben Gill, although some events were observed at the Oxbow (Fig. 2c, d). At the Gauging Station, mean SSC was 1.55 mg l^{-1}, with the maximum recorded on the first day after the reconnection of Ben Gill (04/10/2014, Fig. 2c) and estimated at over 1700 mg l^{-1} (i.e. the upper limit of the turbidity-meter). Maximum SSC at the Oxbow (800 mg l^{-1}) was also recorded on the first day after the reconnection; here, the mean for the study period was 3.00 mg l^{-1}. High SSC events recorded at the Gauging Station were also visible at the Oxbow (Fig. 2c, d), although the latter experienced a higher number of lower magnitude events.

Uncertainties in the calculation of SSL (E_{SSL}) were determined to be ± 8.3%. SSLs and water yields (Fig. 3) were generally highest in autumn and lowest in summer, apart from summer 2016 which saw high flow events (due to intense

Table 1 Flood magnitude and frequency in the River Ehen, and connection patterns in Ben Gill during sampling periods *a* to *l*

Sampling period	River Ehen		Ben Gill		Average duration of connection	Type of scenario dominant	Effects on in-channel storage
	Number of events	Peak flow $m^3 s^{-1}$	Number of connections	Number of days connected	days		
a	3	7.21	Pre-reconnection				Shows uncertainty of method and stochastic variability
b	3	11.7	1	8.17	8.17	Scenario 2 (extreme SSCs)	Significant deposition
c	8	18.2	2	17.52	8.76	Scenario 3	Small removal
d	16	27.8	9	15.43*	1.71*	Scenario 2 and 3	Gradual build-up of storage
e	6	23.7	6	14.58	2.43	Scenario 2	
f	10	13.7	12	10.36	0.86	Scenario 2	
g	0	1.21	1	0.27	0.27	Scenario 1	Shows uncertainty of method and stochastic variability
h	2	5.08	3	1.47	0.49	Scenario 1	Sharp increase in storage
i	18	54.0	28	19.81	0.71	Scenario 1 and 2, then 2 and 3	Potential build-up of storage (though no data), then significant but selective removal of fines
j	15	24.3	24	27.00	1.13	Scenario 3	Storage remains constantly ~ 2× higher than pre-reconnection conditions, but fluctuations limited by relative balance between each scenario
k	3	13.7	7	10.27	1.47	Scenario 2 and 3	
l	10	10.9	10	8.70	0.87	Scenario 1, 2 and 3	

Average duration of connection: 1.27 days (1 day 6 h)

Minimum: 0.04 days (~ 1 h). Maximum: 13.69 days (13 days 16 h)

*The duration of events 4, 5, 6 and 8 could not be defined precisely due to the absence of photographic evidence. The duration of these events was estimated as the mean duration of all other recorded events rainfall) in late August and early September (Fig. 2). On average, SSL at the Oxbow was two times higher than at the Gauging Station (between 1.5 and 4.5 times higher; Fig. 3 and Table 2).

A larger fraction of the SSL was transported in a shorter time at the Gauging Station than the Oxbow (Fig. 4a); thus, fine sediment transport at the Gauging Station was characterised by shorter, more intense throughputs of material. If input from upstream was the only driver of SSL in the lower reach, the transport duration curves for the two stations would be more or less identical. That they are different is evidence of the contribution of additional sources in the lower reach, while the nature of the difference indicates that these new sources deliver material in a more diffuse way, extending over longer periods of time.

Cumulative SSLs at the two monitoring stations showed broadly similar patterns (Fig. 4b); both increased progressively over the period, generally ran parallel and sometimes coincided. However, notable breaks in slope occurred in February–March 2015 and November–December 2015. For all of these breaks, the more marked increase at the Gauging Station allowed the yield here to re-join that at the Oxbow, which because of more continuous increases had advanced more. However, the timing of these ‘catch-up’ events was not consistent. The departure observed in January–February 2015 was quickly recovered during period *e,* when the average duration of connection of Ben Gill was high (i.e. 2.43 days). In 2016, however, the departure observed in December–February was followed by a relatively dry spell (March to August, Fig. 2a). Only after the last sampling occasion (T13) did another episode of high SSCs at the Gauging Station occur, allowing the cumulative SSL to re-join that of lowermost station.

3.3 In-channel sediment storage

3.3.1 Quantitative changes over time

The storage of in-channel fine sediment varied considerably over a number of spatial and temporal scales during the study period. Changes in total storage between successive sampling occasions ranged from -5.56 ± 1.56 to $+3.24 \pm 0.91$ t (Table 3). Decreases were associated with major flood events (notably November and December 2015) while the most marked increase followed immediately from the reconnection of Ben Gill (October 2014). Overall storage of fines remained rather constant following the December 2015 floods (between 3.04 ± 0.85 and 3.61 ± 1.01 t), although values were appreciably higher than the average preceding the reconnection (*c.*1.80 ± 0.50 t).

Average storage over the study period was 475 g m^{-2}, although this varied considerably between morphological units and periods (from 15.1 to 2140 g m^{-2}; Fig. 5). There were some significant temporal patterns (ANOVA, $P < 0.0001$. $F = 5.387$, df = 12), with values of storage on sampling occasion T3 (post-reconnection) significantly higher than T1 and 2 (pre-reconnection) (Tukey’s test, $P = 0.03$) and sampling occasion T10 different to T9 (Tukey’s test, $P = 0.003$). These changes were particularly noticeable in the pool (Fig. 5). Mean storage values in the pool were significantly greater than in the other two units (ANOVA and Tukey’s tests: pool-riffle $P < 0.0001$, pool-plane bed $P < 0.0001$), while the riffle and plane bed did not differ ($P = 0.065$). The magnitude of variation in storage was lower in the riffle (coefficient of variation: Pool = 0.46, Riffle = 0.26, Plane Bed = 0.50).

Fig. 3 Suspended sediment loads (bars) and water yield (line) at each of the monitoring, at a seasonal scale

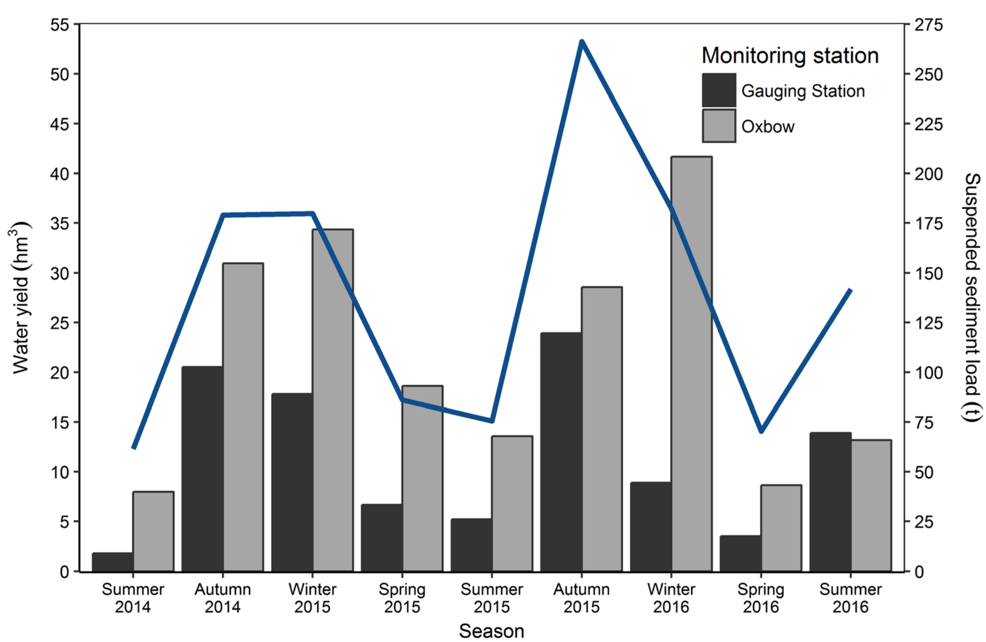

Table 2 Summary statistics of flow and sedimentary conditions in the Ehen during to sampling periods a to l

Sampling period	Number of days	Q_{max}	Q_{mean}	WY	Gauging Station			Oxbow		
					SSL_{max}	SSL_{mean}	SY	SSL_{max}	SSL_{mean}	SY
		$m^3\ s^{-1}$		hm^3	kg 15 min^{-1}		*t*	kg 15 min^{-1}		*t*
a	27	7.21	2.42	5.64 ± 0.45	19.1 ± 1.6	1.31 ± 0.11	3.40 ± 0.3	107 ± 8.9	8.46 ± 0.70	21.9 ± 1.8
b	52	11.7	2.35	10.5 ± 0.8	3280 ± 270	11.0 ± 0.9	55.0 ± 4.6	2050 ± 170	19.5 ± 1.6	97.4 ± 8.1
c	33	18.2	5.34	15.2 ± 1.2	634 ± 53	11.4 ± 1.0	36.0 ± 3.0	626 ± 52	18.2 ± 1.5	57.6 ± 4.8
d	92	27.8	3.98	31.6 ± 2.5	597 ± 50	4.72 ± 0.39	41.7 ± 3.5	878 ± 73	13.6 ± 1.1	120 ± 10
e	29	23.7	6.01	15.1 ± 1.2	1940 ± 160	19.9 ± 1.7	55.4 ± 4.6	1980 ± 160	33.1 ± 2.8	92.1 ± 7.6
f	88	13.7	2.47	18.8 ± 1.5	1200 ± 100	4.21 ± 0.35	35.6 ± 3.0	1080 ± 90	9.55 ± 0.79	80.7 ± 6.7
g	14	1.21	1.00	1.21 ± 0.10	219 ± 18	2.52 ± 0.21	3.38 ± 0.28	76.5 ± 6.4	3.03 ± 0.25	4.08 ± 0.34
h	25	5.08	1.93	4.18 ± 0.33	1310 ± 110	4.84 ± 0.40	11.6 ± 1.0	755 ± 63	7.77 ± 0.64	18.7 ± 1.6
i	144	54.0	4.01	49.9 ± 4.0	1410 ± 120	7.21 ± 0.60	99.7 ± 8.3	1320 ± 110	15.7 ± 1.3	217 ± 18
j	85	24.3	6.49	47.7 ± 3.8	1100 ± 91	9.40 ± 0.78	76.7 ± 6.4	1610 ± 133	20.7 ± 1.7	169 ± 14
k	86	13.7	2.00	14.9 ± 1.2	250 ± 21	1.96 ± 0.16	16.2 ± 1.3	269 ± 1.3	3.52 ± 0.29	29.1 ± 2.4
l	68	10.9	2.39	14.0 ± 1.1	331 ± 27	2.25 ± 0.19	14.7 ± 1.2	310 ± 1.2	4.10 ± 0.3	26.8 ± 2.2

Q discharge, *WY* water yield, *SSL* suspended sediment load, *SY* sediment yield

3.3.2 Flow asynchronicity and its influence on fine sediment transport and storage

The regulation by Ennerdale Water and its 1.3-m high weir has subtle but important effects on the timing of flow events in the Ehen relative to those in Ben Gill. Although high flow events still occur in the Ehen (Fig. 2a), the number and magnitude of small- to medium-sized events are controlled by the weir. The compensation flow outlet controls flows when lake levels are below weir crest, with only periods of more prolonged or intense precipitation capable of increasing lake levels above weir crest and hence increasing discharge in the Ehen. These

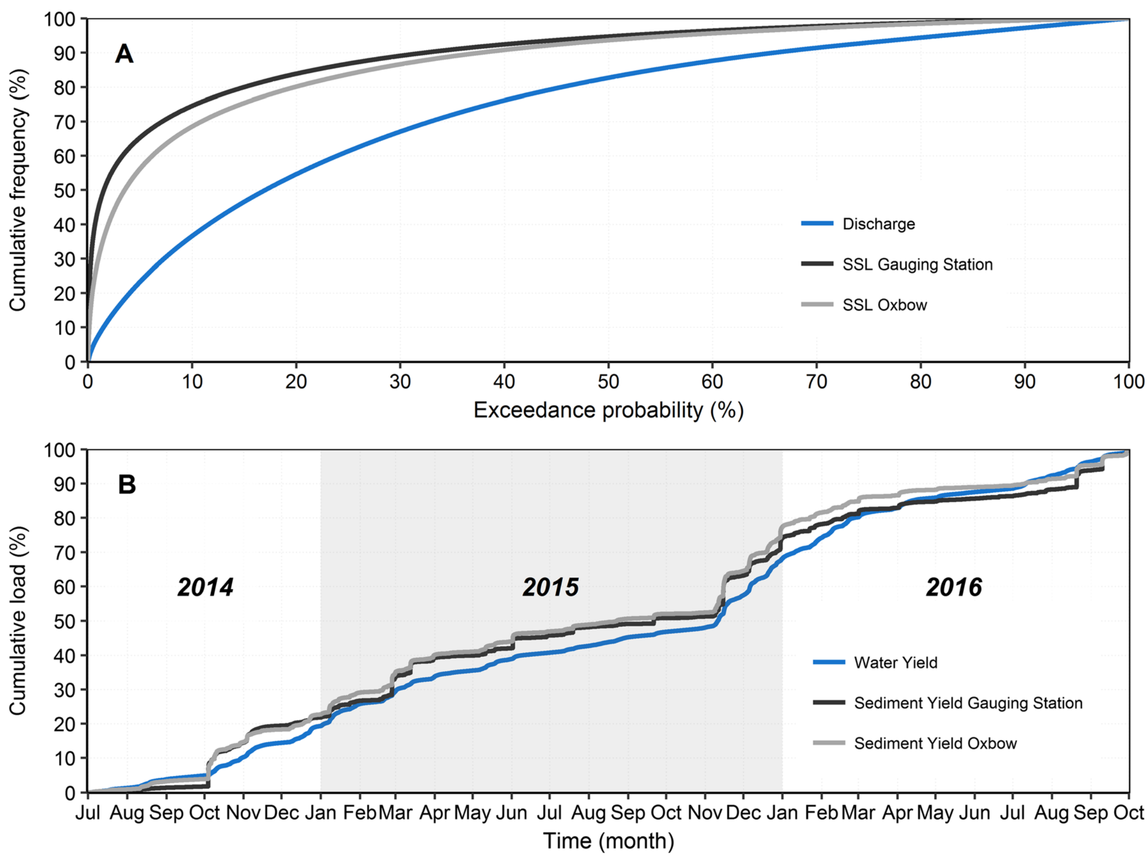

Fig. 4 **a** Transport duration curves, presented as the cumulative frequency of exceedance probabilities, for discharge and suspended sediment load at the two monitoring stations. **b** Cumulative load over time for water yield and suspended sediment yields at the monitoring stations

Table 3 Summary statistics of water yield, in-channel storage, suspended sediment loads and sediment budget for each sampling period

Sampling period	Water yield	In-channel storage	Sediment load		Sediment budget			
	Gauging station	Upstream reach[1]	Gauging station	Oxbow	Change in in-channel storage[2] upstream reach	Transfer[4] into downstream reach[3]	Fraction of in-channel storage in budget of upper reach	Fraction of locally soured sediments[4] in budget of lower reach
	hm^3	*t*	*t*	*t*	*t*	*t*	%	%
a	5.64 ± 0.45	2.11 ± 0.59	3.40 ± 0.28	21.9 ± 1.8	+0.31 ± 0.09	18.5 ± 1.5	9.1 ± 2.6	84.5 ± 7.0
b	10.5 ± 0.8	5.34 ± 1.50	55.0 ± 4.6	97.4 ± 8.1	+3.24 ± 0.91	42.5 ± 3.5	5.9 ± 1.7	43.6 ± 3.6
c	15.2 ± 1.2	3.43 ± 0.96	36.0 ± 3.0	57.6 ± 4.8	− 1.91 ± 0.53	21.6 ± 1.8	5.3 ± 1.5	37.4 ± 3.1
d	31.6 ± 2.5	3.58 ± 1.00	41.7 ± 3.5	120 ± 10	+0.15 ± 0.04	78.3 ± 6.5	0.4 ± 0.1	65.2 ± 5.4
e	15.1 ± 1.2	4.72 ± 1.32	55.4 ± 4.6	92.1 ± 7.6	+1.14 ± 0.32	36.6 ± 3.1	2.1 ± 0.6	39.8 ± 3.3
f	18.8 ± 1.5	5.08 ± 1.42	35.6 ± 3.0	80.7 ± 6.7	+0.36 ± 0.04	45.1 ± 3.7	1.0 ± 0.3	55.9 ± 4.6
g	1.21 ± 0.10	4.90 ± 1.37	3.38 ± 0.28	4.08 ± 0.34	− 0.18 ± 0.32	0.70 ± 0.06	5.3 ± 1.5	17.1 ± 1.4
h	4.18 ± 0.33	7.46 ± 2.09	11.6 ± 1.0	18.7 ± 1.6	+2.56 ± 0.72	7.03 ± 0.58	22 ± 6.2	37.7 ± 3.1
i	49.9 ± 4.0	1.90 ± 0.53	99.7 ± 8.3	217 ± 18	− 5.56 ± 1.56	117 ± 9	5.6 ± 1.6	54.0 ± 4.5
j	47.7 ± 3.8	3.31 ± 0.93	76.7 ± 6.4	169 ± 14	+1.41 ± 0.39	92.2 ± 7.7	1.8 ± 0.5	54.6 ± 4.5
k	14.9 ± 1.2	3.04 ± 0.85	16.2 ± 1.3	29.1 ± 2.4	− 0.27 ± 0.08	13.0 ± 1.1	1.7 ± 0.5	44.5 ± 3.7
l	14.0 ± 1.1	3.61 ± 1.01	14.7 ± 1.2	26.8 ± 2.2	+0.57 ± 0.16	12.1 ± 1.0	3.9 ± 1.1	45.1 ± 3.8
Total	238 ± 19	50.3 ± 14.1	450 ± 37	934 ± 78	+1.81 ± 0.51	490 ± 41	3.9 ± 1.1	52.0 ± 4.3

[1] Reach between the confluence of Ben Gill and Bleach Green Gauging Station

[2] Change in in-channel sediment storage calculated as the difference between storage at time *t* and time *t*−1

[3] Reach between Bleach Green Gauging Station and the Oxbow

[4] Locally sourced sediment (i.e. lateral inputs, bank erosion, release from the bed) of the downstream reach calculated as the difference between the sediment load input (Gauging Station) and output (Oxbow)

factors can generate temporal mismatch between high flows in the Ehen and episodes of flow in Ben Gill. Localised rainfall events may also contribute to this mismatch.

Using the time-lapse camera facing the confluence, a conceptual framework of flow scenarios was developed to characterise the relationship between flows in the Ehen and Ben Gill (Fig. 6). Scenario 1 is 'total asynchronicity'. This scenario follows (a) episodes of long-lasting low flows in the Ehen, when rainfall over the headwater areas is just enough to re-fill the reservoir but not enough to overspill the weir, while (b) the rainfall is sufficient to trigger flows in Ben Gill and its connection to the Ehen. This scenario can be exacerbated by the sometimes localised nature of precipitation, which may mean that Ben

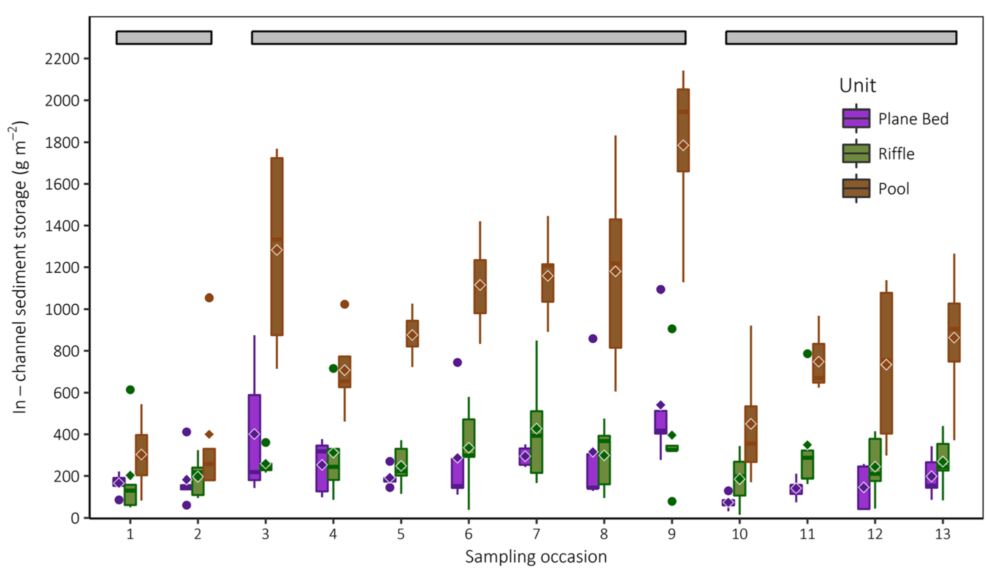

Fig. 5 Boxplot of in-channel sediment storage (combined levels A1 and A2) per sampling occasion. Coloured diamonds represent mean values and coloured points show outliers. Horizontal bars above the plot link successive dates that did not differ significantly, i.e. a break in the bar means significant difference between two successive sampling occasions

Gill receives more rain than the upstream catchment which feeds into Ennerdale Water. This leads to high SSCs in the Ehen. Scenario 2 is 'partial synchronicity'. Here, the difference in response time to rainfall between Ben Gill and the Ehen means that SSC rises sharply once Ben Gill starts flowing (Fig. 6(b)), but concentrations are later diluted as Q increases in the Ehen and the inputs from the tributary decrease (exhaustion of sediment supply from the tributary). Scenario 3 is 'total synchronicity'. In this scenario, Q in the Ehen increases prior to the connection of Ben Gill. Once Ben Gill starts flowing and delivering water, sediment from the tributary is rapidly diluted and SSCs remain low throughout the event. Scenario 3 occurs, for example, when lake levels are already high and precipitation causes rapid weir overspill.

These scenarios represent a useful framework for understanding changes in SSC and storage related to rainfall and associated increases in Q. They are used below to conceptualise changes occurring between successive sampling intervals during the study period (Fig. 2a). Tables 1 and 2 provide key hydrological and sedimentary data for the intervals, as well as comments on the flow scenarios prevailing during each one. Key points are summarised below.

Period *a* captures conditions immediately prior to the reconnection, with no marked high flow events in the Ehen. SSCs were very low (< 10 mg l^{-1}) and apparent changes in mean storage were very limited ($+ 0.31 \pm 0.09$ t).

The opening of the newly restored and connected Ben Gill channel occurred during period *b*. The very intense but localised rainfall that occurred on the first day the channel was connected (> 120 mm over 24 h) resulted in a prolonged period of flow in Ben Gill (one event, 8 days long) and medium flows in the Ehen ($Q_{max} = 11.70$ m^3 s^{-1}). This type 2 scenario resulted in high SSCs and a marked increase in total storage over the reach ($+ 3.24 \pm 0.91$ t), which was especially evident in the pool (mean increased from around 400 to 1300 g m^{-2}).

Period *c* is an example of scenario 3, when flows in the Ehen and Ben Gill are synchronous. Although there was material being delivered by Gen Gill, the discharge in the Ehen (always greater than 5 and occasionally more than 10 m^3 s^{-1}) appeared competent, with a net reduction in storage occurring (from 5.34 ± 1.50 to 3.43 ± 0.96 t).

Conditions were broadly similar over periods *d* to *g*. There were some high SSC events associated with periods when Ben Gill was connected, but despite some medium to high discharges in the Ehen, in-channel storage gradually increased over the winter, spring and early summer. These periods were characterised by a succession of type 2 and type 3 scenarios, with the prevalence of deposition indicated by the gradual increase in storage.

Period *h* illustrates the extreme processes associated with scenario 1. The lack of competent flow ($Q_{max} = 5.1$ m^3 s^{-1}) associated with high SSCs (e.g. $SSL_{max} = 1.30$ t 15 min^{-1}) caused by flow events in Ben Gill allowed fine sediment to deposit on the bed of the Ehen (an increase of 2.56 ± 0.72 t storage). This represents the highest value of storage measured during the study period (reaching 7.46 ± 2.09 t).

The first part of period *i* experienced hydro-sedimentary conditions similar to period *h*, with low peak flows and frequent connections of Ben Gill. This is likely to have contributed to a further increase in storage, although no sampling was performed to confirm this. However, period *i* ended with a series of high Qs ($Q_{max} = 54.0$ m^3 s^{-1}, three successive events higher than 27.8 m^3 s^{-1}, i.e. highest peak Q of period *d*). Among the *c*.20 flow events recorded in Ben Gill during the latter part of period *i*, only one was of type 2 scenario; all other events were type 3. These very wet conditions led to a significant decrease in storage ($- 5.56 \pm 1.56$ t), and a decrease in variability, to levels similar to those prior to the reconnection. This shows the potential of such extreme events to remove stored fine material from all units.

Period *j* showed hydro-sedimentary conditions similar the latter part of period *i*, but with lower peak Qs ($Q_{max} = 24.3$ m^3 s^{-1}). Ben Gill was connected to the Ehen on numerous occasions during the period (24), but most events were of type 3 scenario (only 2 were of type 2). Despite frequent high flows, the channel experienced an increase in storage ($+ 1.41 \pm 0.39$ t), highlighting the inability of the system, under some conditions, to convey all material supplied by Ben Gill.

The end of the study period (periods *k* and *l*) saw the channel experiencing mostly scenario 2 and 3 events, apart from a couple of scenario 1 events in June 2016 (see illustration in Fig. 6). However, average storage tended to stabilise around 3.6 ± 1.0 t which, despite being higher than pre-reconnection conditions (twofold increase), was controlled by the relative synchronicity between flows in Ben Gill and high Q in the Ehen.

3.3.3 Changes in grain-size and organic content over time

The average amount of organic matter stored in the riverbed varied between 5 and 71 g m^{-2}, with values always greatest in the pool. The organic component of the fine sediment ranged between 3.3 and 11.5% (average = 5.7%). There was no relationship between the proportion of fine material comprised of organic matter (% of total) and the total amount of organic matter (g); thus, variations in the proportion of organic matter were not a direct response to variations in the absolute amount of organic material ($r^2 = 0.03$, $P > 0.05$).

The majority of the stored sediment consisted of sand (average = 67.6%), with silt quite abundant (average = 26.5%) and clay usually minor (average = 5.9%). There were no significant changes in median particle size of the stored sediment associated with the opening of Ben Gill (Friedman's Test: $p = 0.073$). Median particle size (D_{50}, average = 164 μm, range = [80–298]

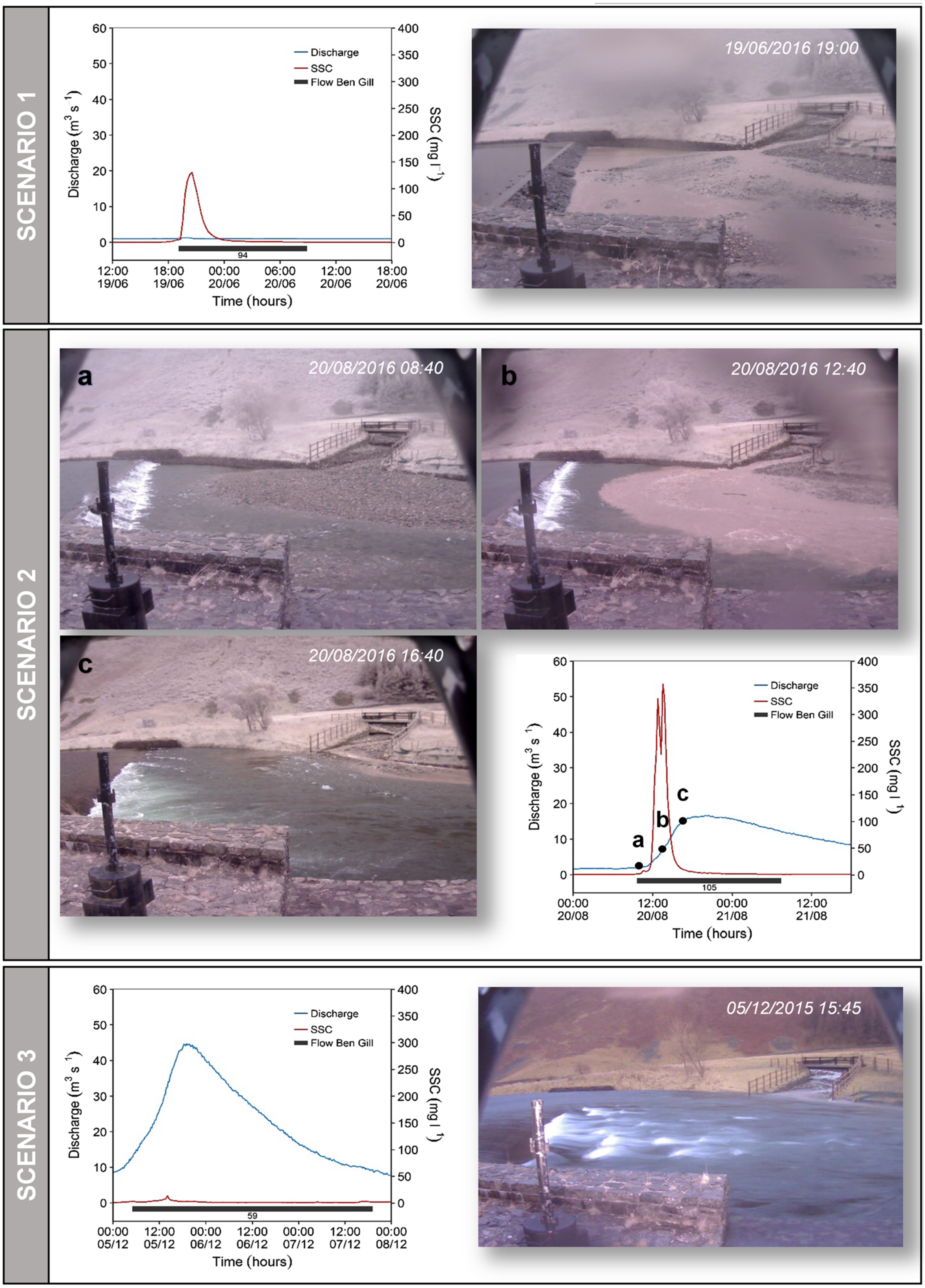

Fig. 6 Different scenarios observed at the confluence of Ben Gill (stream facing the camera) with the River Ehen (flowing from the left) since the reconnection (see text for more details on each scenario). Discharge (blue line) and Suspended Sediment Concentration (SSC, red line) are measured at the Gauging Station. Flows in Ben Gill (grey bar) are determined from time-lapse photos

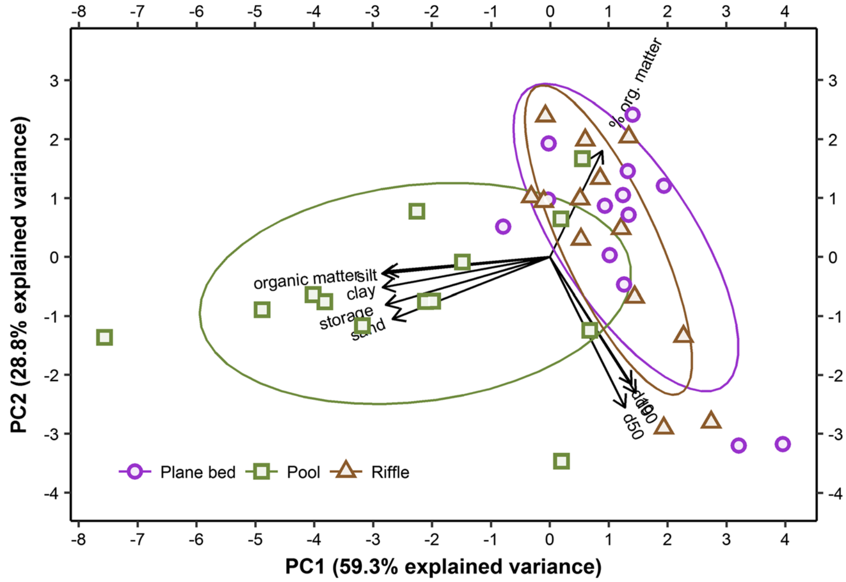

Fig. 7 PCA ordination of the characteristics of the stored fine sediment. Symbols and ellipses are used to group the samples by morphological unit. Organic matter = absolute amount of organic matter; silt/sand/clay = absolute amount of each fraction; D10/D50/D90 = particle size of each quantile; % org. matter = proportion of organic matter

μm), D_{10} (11 [6–32] μm) and D_{90} (495 [285–862] μm) reflect the wide range of particle sizes collected from the bed.

The PCA used to characterise the overall characteristics of stored sediment highlighted the distinctiveness of the pool, and the fact that the other units were very similar (Fig. 7). Together the two principal components explained approximately 88% of the variance in sediment characteristics, with the first component (59.3%) clearly driven by amount of material (total and amounts in the various size fractions) and the second (28.8%) driven by the relative organic content (% of total) and sizes of the material. The separation of the pool was mainly due its greater amount of organic matter and the total amount of stored material. Arrow lengths for the variables were largely the same, so no particular sediment characteristics were more important for distinguishing between the samples than others. The exception was percent organic which had a shorter arrow than all the others, indicating that it differed less between the samples.

The PCA also emphasised the relations between total sediment and the total and percentage of organic material. Samples with large quantities of fine sediment also had higher absolute amounts of organic material. The arrows for absolute and percentage of organic sediment point in opposite directions; thus, in samples with large amounts of organic sediment, this material makes up a relatively small proportion of the total fine storage. Arrows for all size percentiles point in the same direction (D_{90}, D_{50} and D_{10}), so samples with a large median size also had a large D_{90}, etc.

The maximum percentage of organic matter (10.2%) was observed prior to the reconnection. Subsequently, the amount organic matter remained relatively low, with a peak of 6.1% in June 2016 (T12). This, along with the direction of the two arrows on Fig. 7, suggests that morphological units differ little in the percentage of organic material when total amount of stored sediment is high, but differ in percent organic content when fines are less prevalent.

3.4 Sediment budgets

In the upper reach, the release of sediment from the riverbed (Table 3) was responsible for a minimum average of 3.9% of the total fine sediment budget (3.2% year 1, 4.7% year 2). Values for individual sampling periods ranged from 0.4 to 22% (Table 2). Low values are characteristic of limited changes in storage, (e.g. periods *d* and *f*) while high values correspond to periods of more intense activity (removal or deposition, such as periods *h* and *i*).

Input from directly upstream represented an average of 48% of the suspended sediment budget of the lower reach (i.e. difference between suspended sediment yield at the Oxbow and that of the Gauging Station); the remaining 52% is therefore taken to be composed of lateral inputs, resuspension from the riverbed and bank erosion (Table 4). Values for individual sampling periods varied between 17.1 and 65.2% after reconnection, but with the highest values being for the pre-reconnection period (84.5%). The relative proportion of each of the processes is unknown, although we hypothesise

Table 4 Reach-scale suspended sediment budgets for the study section

	Upper reach (%)	Lower reach (%)
Lateral input*	39.4 ± 5.0	52 ± 4.3
In-channel storage	3.9 ± 1.1	
Bank erosion	56.7 ± 6.1	
Input from upper catchment		48 ± 4.0

*Lateral input for the upper section consists solely of the newly reconnected ephemeral tributary Ben Gill that resuspension from the riverbed will be of a similar order of magnitude to the upper reach (i.e. *c*.4%). This leaves a potentially high proportion of the suspended sediment budget generated by lateral input from ditches and non-perennial tributaries, despite the relatively short distance between the monitoring stations (2.52 km) and limited additional catchment area (+ 2.5 km^2).

4 Discussion

The reconnection of Ben Gill aimed to restore the delivery of water and coarse sediment to the Ehen, and within a year there were signs that this was happening (Marteau et al. 2016). However, the reconnection has also changed suspended sediment dynamics in the river (Marteau et al. 2017). The current paper aimed to assess the total sediment budget of the reach studied by previous authors, along with an adjacent reach further downstream, with a particular focus on in-channel bed storage and how the degree of synchronicity between flows in Ben Gill and the Ehen influences the movement of fine sediment through the system.

4.1 Flows and suspended sediment dynamics

Despite being regulated by the lake and weir, the hydrology of the River Ehen has retained a certain degree of variability. Regulation mostly affects low flow conditions when water in the lake does not overspill the weir and flows downstream are therefore controlled by the compensation release. Hydrological statistics for the study period are slightly higher than long-term averages, primarily reflecting an increase in compensation flow since 2014 but also the very wet winter of 2015. Ben Gill is a non-perennial stream with a small catchment area. During the study period, it flowed for approximately the same percentage of time as the period covered by Quinlan et al. (2015a). Flows in Ben Gill respond rapidly to local rainfall events; it is a flashy stream, with flows lasting from just few hours to few days.

Total sediment loads in the two reaches were increased following the reconnection. Patterns of sediment transport differed slightly between the two monitoring stations: SSLs were higher at the downstream station (Oxbow), where transport was characterised by events of higher frequency but lower magnitude. This reflects the difference in the nature of sediment sources (Fig. 4b also illustrates this difference). Cumulative SSL at the Oxbow departs from that of the Gauging Station in the wet winter months, when surface run-off is most frequent and creates low magnitude but frequent SSC events at the Oxbow. The cumulative SSL curve at the Gauging Station only ‘catches-up’ following repeated or long-lasting periods of delivery from Ben Gill.

Hydro-geomorphologically, the upper reach is controlled predominantly by flashy inputs from Ben Gill, while the lower reach receives sediment from ditches and surface run-off, which can be triggered by smaller rainfall events. It is also possible that human-induced sources of fine material (e.g. septic tanks) may contribute to this increase in sediment input, but in ways that are independent of rainfall or discharge. The catchment area at the Oxbow is only 2.5 km^2 greater than at the Gauging Station, but this additional area contributes 185 ± 15 t km^2 y^{-1}, similar to the contribution of Ben Gill for the upper reach (181 ± 15 t km^{-2} y^{-1}, Marteau et al. 2017). Such specific sediment yields fall within the upper range of values found in the UK (e.g. long-term average flux; 5th and 95th percentiles of 5.4 and 107.7 t km^{-2} y^{-1}, respectively, Worrall et al. 2013) but are in line with those of agricultural and human-modified catchments (up to 488 t km^2 y^{-1}, Foster and Lees 1999).

4.2 In-channel sediment storage

Changes in fine sediment storage on the bed of the Ehen varied appreciably over time and space. The pool, where conditions are most favourable for deposition, experienced higher volumes of storage compared to the plane bed and riffle (e.g. mean maximum storage > 1800 g m^{-2}) but was also significantly different in terms of the characteristics of the stored sediment. Here, stored sediment contained more organic matter (up to 71.5 g m^{-2}). Although the riffle and plane bed did not differ significantly in terms of quantity and grain-size and organic composition, variations in storage were greater in the plane bed. The riffle, where velocities remain relatively higher even at low flows, appears to be less sensitive to deposition and removal of fine sediments. This unit was also the only one where deposition of fresh and loose gravel was observed over the course of the study. Fresh deposits, originating from Ben Gill, usually contained little or no fine sediment.

Maximum storage of fine sediment peaked approximately a year after the reconnection of Ben Gill, reaching 7.46 ± 1.38 t, representing a 350% increase. By the end of the study, storage averaged 3.60 ± 0.81 t; although much less than the peak, this still represents a twofold increase compared to the period immediately pre-reconnection (summer 2014) and is also higher than the 2010–12 period monitored by Quinlan et al. (2015a).

Despite this increase, in-channel fine sediment storage in the Ehen is not particularly high compared to examples found in the literature. Within a British context, reported values vary between 40 g m^{-2} (tributary of the Piddle, Collins and Walling 2007b) and 80,000 g m^{-2} (River Severn, Walling and Quine 1993). Most reported average values are between 200 and 2000 g m^{-2} (e.g. Walling et al. 1998, 2006; Owens et al. 1999; Wilson et al. 2004; Collins et al. 2005; Collins and Walling 2007b). High values of storage tend to be found in small agricultural catchments (e.g. Walling et al. 2002;

23,400 g m^{-2}) or lowland rivers (e.g. Heppell et al. 2009; 66,800 g m^{-2}) while low values are found in small urbanised catchments (e.g. West Midlands, Lawler et al. 2006; 50–110 g m^{-2}) and chalk streams (Acornley and Sear 1999). In the upper Ehen, average storage ranged from 224 (T1) to 907 g m^{-2} (T9) and included all particles between 0.012 and 2 mm. This corresponds to the lower range of values found in the literature, and is typical of rivers with limited sedimentary activity. Many authors consider fine sediment as being < 63 μm (i.e. silt and clay only) which only represents 32% on average (volume) of the material stored in the Ehen.

Some authors have observed seasonal variations in fine sediment storage, sometimes higher in winter (e.g. Acornley and Sear 1999; Walling and Amos 1999) and sometimes in summer (e.g. Walling et al. 2003; Collins and Walling 2007a, b). Others have observed mixed patterns, arguing for the importance of cycles of vegetation growth and senescence (Heppell et al. 2009) or the greater influence of flow conditions and local channel characteristics (Marttila and Kløve 2014). The latter authors also found that, in a catchment exploited for peat and wood in central Finland, the high volumes of sediment delivered by headwater tributaries were quickly conveyed downstream; similar dynamics have been reported in Mediterranean streams (Francke et al. 2014; Piqué et al. 2014). No seasonal trends were observed in the variations of sediment storage in the River Ehen. Spatial variability increased with increased deposition, and vice-versa, despite the relatively simple morphology of the riverbed. Although the river is capable of removing accumulated fine sediments, significant cleaning was only observed in response to high magnitude, low-frequency events. Thus, the absence of deposition plays a potentially greater role in controlling storage than the removal of fines during floods. This is an important consideration in this regulated system, where water abstraction from the lake can lead to frequent and long-lasting periods of low flow (i.e. compensation flows).

The average fraction of sand stored in the Ehen (67%) is consistent with findings from lowland vegetated rivers (e.g. Heppell et al. 2009), although the median particle size (D_{50} = 164 μm) is greater than other studies (e.g. Marttila and Kløve 2014; 7–60 μm). The major flow events of November–December 2015 influenced the relative proportions of sand and silt across the upper reach, with the proportion of silt being reduced to 14.5% and the proportion of sand increasing to 81.3% (clay ~ unchanged, 4.2%). It is noticeable, however, that this change cannot be attributed to the break-up of the paved layer, despite the magnitude of the floods during this period (highest Q = 54.0 m^3 s^{-1}, 30-year return period). The surface layer remained stable and retained a fair proportion of the sands and clays, releasing mostly the medium fraction of the finer particles (i.e. 4 to 62 μm). During their study of controlled releases of water under different antecedent conditions, Petticrew et al. (2007) found that the presence of an armour layer helped reduce the loss of fine sediment and it is likely that the paving in the Ehen exerts a similar influence on sediment loss at most flow conditions. We hypothesise that pore space in the pavement is reduced by its level of compaction; thus, sands may be too coarse, and clay too cohesive, to be washed out of the matrix. Rather than size-selective entrainment, the process occurring in the Ehen may therefore be best considered as size-selective retention. Additionally, bed conditions rapidly returned to pre-high flow conditions as more sediment was supplied to the river, coinciding with less competent discharges.

The organic fraction of stored sediment in the Ehen was rather low (< 6% post-reconnection) compared to other studies (e.g. 9–17%, Walling et al. 1998; 30%, Marttila and Kløve 2014). The percentage organic fraction did not play an important role in discriminating between the three morphological units present in the study reach when volumes of stored sediments were high, but differed when the bed was cleaner, i.e. following high flow events, when less fine sediment was present.

4.3 Fluvial sediment budget and sources of material

Despite fluctuations over time, reflecting net losses associated with high Q events, data suggest that in-channel storage of fine sediment in the Ehen has increased since the reconnection in October 2014 (from 1.8 ± 0.70 to 3.6 ± 0.81 t). Generally, the contribution of in-channel storage to sediment budgets varies greatly in the UK (e.g. Exe, 1.6%; Lambert and Walling 1988; Severn, 2%; Walling and Quine 1993; Leadon, Tone and Torridge, 0.9 to 1.5%; Wilson et al. 2004) and can be appreciably higher than the Ehen (e.g. Frome and Piddle, 18–55%; Collins et al. 2005; Tern, Pang and Lambourn, 21–38%; Collins and Walling 2007a). The contribution of stored sediment to the sediment budget in the Ehen is thus rather limited compared to other rivers in the UK. However, it has decreased since the reconnection (8.9%, period *a* of this study; estimated as 11.9%, from Quinlan et al. (2015b), to 3.9% on average in this study). In fact, the increase in storage and release of fines from the bed belies the large increase in SSL (+ 65%) following the reconnection. It should also be noted that the total amount of sediment moving into and out of storage in the study reach is likely to be substantially greater than the estimates of mean total storage, due to the ‘snapshot’ nature of the sampling methods.

In their study of the conditions in the Ehen prior to the restoration work, Quinlan et al. (2015a) argued that sedimentary activity was very low, and sediment dynamics were likely to be driven mostly by locally sourced sediment; i.e. material eroded from the banks or re-suspended from the bed. Over the 40-year period that Ben Gill was disconnected, the lack of coarse sediment supply and the winnowing of relatively fine particles during high flows resulted in the appearance of a well-developed armour layer in the Ehen, becoming more and more resistant to even very high discharges. Marteau et al. (2017) estimated approximately 40% of the total suspended sediment yield in the upper reach is now supplied by Ben Gill, with the remaining percentage corresponding to input from the upper part of the catchment together with very localised bank erosion within the reach.

The simple conceptual framework used to identify the different flow scenarios proved to be helpful to characterise suspended sediment dynamics in the Ehen, with changes in storage controlled by the degree of synchronicity between flows in the main-stem and those in Ben Gill. Scenario 1 results in deposition while scenario 3 allows the system to remove part of the stored fine sediment (Table 1). Scenario 2 can have greater or lesser effects on storage, depending on the magnitude of the associated discharge. Scenario 3 events, especially when associated with high peak flow (i.e. above 20 $m^3 s^{-1}$) are responsible for the removal of stored sediment. During the 2-year study period, the most significant changes in storage followed two key events: the reconnection of Ben Gill (Scenario 2, period *b*) which corresponded with a very high SSC event, and a series of very high discharges (Scenario 3, period *i*) brought by two successive storms in November and December 2015. Both storms triggered significant changes in storage in the channel and so were useful to help understand the processes of deposition and removal of fine sediment in the system.

Period *a*, although short in duration, highlighted the major role played by lateral inputs to the lower reach prior to the reconnection of Ben Gill (> 80% of sediment budget). The ratio has decreased since the reconnection (average *c*.50%). Although lateral inputs were not specifically quantified (i.e. budget estimates are based on suspended sediment monitored at the Gauging Station and the Oxbow), such sources of fine material (e.g. bank erosion) become increasingly important with increasing distance downstream. This conclusion is based on the magnitude of difference between the two reaches set against the limited uncertainties of the computed SSL (± 8.3%).

4.4 Management perspective

The nature of the system described in the study is unusual, with the juxtaposition of a highly dynamic ephemeral stream discharging just downstream from an impoundment. The flow scenarios reported here reflect this juxtaposition, not just at the present time but potentially also before the tributary was disconnected. The extreme difference between the flow scenarios provides a wide gradient which has resulted in marked differences in the dominant process over the study period (sometimes rapid sediment accumulation, sometimes loss). In turn, the different fluvial processes occurring in response to the flow scenarios provides critical information to aid the management of the Ehen, especially from an ecological perspective.

The occurrence of events with total or partial asynchronicity (especially when flows in the Ehen are low) represents the most ecologically stressful ones. These phenomena can cause high SSCs, sometimes long-lasting, and are more likely to generate higher rates of deposition. High duration and magnitudes of deposition are known to be detrimental for pearl mussels. Thus, limited deposition and/or increased removal of fines, which are fundamental to the ecological success of the Ehen restoration project, are dependent on the ability of the river to respond rapidly to rainfall events. Given the characteristics of the system, it appears that focusing on the prevention of deposition may lead to greater success. Indeed, limiting the occurrence of scenario 1 events, by stopping water abstraction for instance, would be easier to implement than enhancing the occurrence of scenario 3 events, which strongly depend on unpredictable periods of high rainfall. Further reduction of suspended sediments in the system could be tackled by looking in more detail at lateral and intermittent sources of sediment, especially for the lower reach of the study section, and applying efforts to control these. Farmlands are known to be an important source of fine sediment for rivers (Montgomery 2007), whether from crop topsoils, farm tracks or well-connected ditches (Collins et al. 2012). The identification of point sources of fine sediment in the Ehen is the subject of an ongoing investigation by the UK Environment Agency and other partners in the restoration project, with the long-term aim of controlling and preventing further degradation of habitat conditions in this section of the river (APEM 2015).

The management of fine sediment in fluvial systems relies on a better understanding of the processes that control transfers as well as magnitude-frequency effects and geomorphic thresholds (Owens et al. 2005). On the one hand, the present study helps provide a better insight into the functioning of the Ehen as a fluvial system. On the other hand, much remains to be understood about the longer-term evolution of the river in response to the reconnection of Ben Gill and ongoing changes to abstraction from Ennerdale Lake and associated changes to the compensation flow. Over the 2 years of this study, the succession of high flows was unable to break the armour layer. However, new pockets of coarse sediments originating from Ben Gill were observed in the upper study reach, showing that the Ehen is not only conveying the finer fraction of the newly delivered sediment. Displacement of the coarser material is likely to be the only means for the riverbed to experience a renewed vertical mixing and, potentially, a renewal (at least partial) of the bed surface texture and structure. Further monitoring of the geomorphic processes at play in the Ehen is required to better appreciate how it will respond to new mobile sediment and altered flows.

5 Conclusions

In supply-limited systems such as the Ehen, lateral inputs can represent a large fraction of the fluvial sediment load. The fine sediment yields of the two reaches reported in this study, located downstream from a lake and its associated weir, are largely controlled by intermittent sources of sediment: an ephemeral tributary for the upper section (Ben Gill) and a network of ditches, small tributaries and surface run-off for the lower section (e.g. farmlands, anthropogenic source points). These inputs are significant, despite the relatively small contributing catchment sizes.

SSCs in the upper reach, and whether or not this material is stored here or conveyed downstream, depend critically on the degree of synchronicity between the ephemeral Ben Gill and the main-stem. The three flow scenarios provide a useful framework to understand the circumstances under which benthic habitat might be sub-optimal for sensitive species, and in turn can help target management efforts to reduce the risks associated with certain combinations of hydrological conditions.

The relative contribution of stored sediment to the Ehen's sediment budget is highly variable and depends on a complex interaction between SSCs and flows, as well as antecedent hydro-sedimentary conditions. Although limited in the River Ehen due to the very stable conditions of the riverbed, at times stored sediment still contributes over 20% of the sediment budget. The variability in SSCs and storage over the 2-year period helps emphasise the intermittent nature of fine sediment transport processes in river channels. The intermittency of these processes in the Ehen is largely a result of flow regulation and the ephemeral nature of one of its main sources of fine sediment.

Bed storage showed cycles of increase and decrease associated with variation in the hydrological regime of the Ehen. Bed storage was higher at the end of the study period than at the beginning. However, it would be premature to assume that this situation will persist, as supply is driven by input from Ben Gill, a stream that is still adjusting to its new configuration, and whose future evolution (degree of erosion) remains unclear. We hypothesise that sediment delivery is still greatly influenced by the erosion of unconsolidated sediments from the Ben Gill alluvial fan, and that this will decrease as the new channel becomes more graded. Moreover, cycles of deposition and removal in the Ehen are likely to be altered by sedimentological and geomorphological changes which occur in response to the delivery of coarse material, as well as hydraulic feedbacks which affect entrainment and settlement.

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